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Multi-Element X-Ray Shields for Spacecraft

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Spacecraft electronics must be shielded against the x-rays of a distant nuclear weapon. The optimum shielding material is a mixture of heavy elements. Rads(Si) are calculated for some materials and thicknesses.

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Multi-Element X-Ray Shields for Spacecraft

Introduction

The defense of the United States has become increasingly dependent upon satellite systems for communications, navigation, and surveillance. In view of this dependence, the Department of Defense and the National Security Council have emphasized the need for military spacecraft capable of surviving radiation exposures.

This report deals with optimization of the shielding against x-rays from exoatmospheric nuclear detonations, a task involving materials of high atomic number, Z. It is easy to shield sensitive materials from low-energy x-radiation. One merely uses a sufficiently massive shield, normally of lead. In the case of spacecraft, it becomes imperative to minimize mass. The shield must, therefore, be of optimum materials and design and be of only adequate thickness.

In considering protection against the x-ray threat, however, one must also be aware of other environmental radiation in the orbits of interest.

Environments

Some military spacecraft operate in the rather benign environment of synchronous equatorial orbits, appearing to be immobile at an altitude of 19,323 nautical miles above a spot on the equator, far above the intense portions of the earth's radiation belts. The requirements for most tasks dictate lower orbits and, indeed, that some spacecraft traverse regions of intense radiation.

The natural radiation in earth orbits consists of protons and electrons, with very few heavy ions. As many of these particles originate in the sun, the radiation level is dependent upon solar activity and the 11-year solar cycle. Satellites must be designed to insure that significant radiation damage does not occur within the planned mission duration. In addition to dose rate and accumulated dose, shield design now must also consider "single event" effects. A single high-energy particle can produce sufficient ionization in a circuit element to upset that circuit -- changing a bit stored in a computer memory is the usual example. The relatively rare heavy ions in cosmic radiation are particularly effective in producing single event upsets.

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As was demonstrated by the Starfish event of 1962, the radiation from an exoatmospheric nuclear test can destroy an unshielded satellite, even if quite remote. Satellites are hit by an intense burst of x-rays and by nuclear gamma rays, followed by neutrons. Charged particles, primarily electrons, are trapped in the geomagnetic field and bombard satellites over a period of weeks to years.

Shields

Optimum defenses against these various radiations require various techniques and materials. Against charged particles, electrons and protons, low-Z materials are best. At modest particle energy, it is primarily a matter of getting the most electrons per unit mass. Aluminum shielding is inherent in spacecraft structures and additional particle shielding is normally also of aluminum (Z = 13). The only notably superior element is hydrogen, with a 1-to-1 ratio of atomic mass units to electrons versus the approximately 2-to-1 ratio for all other elements. Unlike aluminum, an excellent electrical conductor, shielding by hydrogenous compounds does not counter the electromagnetic pulse following a nuclear explosion. In order to minimize the number of penetrating bremsstrahlung x-rays produced in stopping electrons, a low-Z material is again preferable.

For the case of x-rays of about 15 to 150 keV energy, the optimum shielding materials are those of high atomic number, lead (Z = 82) being the commonly-used element. The nuclear gamma rays, of about 1 to 10 MeV, and the fast neutrons are very penetrating. As we are considering the mass restrictions of a spacecraft rather than a battleship, one cannot attenuate the gamma rays or neutrons appreciably. An upper limit to x-ray shielding, therefore, is that amount needed to reduce the x-ray dose to about that of the penetrating radiations.

It is thus seen that spacecraft should have a combination of low-Z and high-Z shielding. The x-rays come from essentially a point source, a fireball small compared to its distance from any survivable spacecraft. They will strike some surfaces normally and survivability considerations must be based on this case. Even a small hole in the shielding is intolerable as the electronic devices in line with that hole will be wiped out. The electron bombardment, on the other hand, is multi-directional because the electrons follow spiral paths almost from pole to pole in the earth's magnetic field and because the satellite changes orientation. The electron shielding calculations thus involve isotropic radiation and a weak area of shielding can be tolerated.

The X-Ray Spectrum

Data on the spectrum of photons from nuclear weapons is meager and mostly classified. Although a nuclear explosion is far from a steady state event, the radiation is often taken to be that from a homogenous hot body. The only parameter for the spectral shape is the temperature. A "temperature" of kT = 15 keV is used here.

The equilibrium spectrum of a body is that of Planck radiation. The spectrum has acquired the name "black body radiation", the radiation from an isothermal object which absorbs all incident radiation. The physical realization of a "black body" is a cavity with a small hole to the exterior.

The radiation spectrum formula and, more particularly, the novel assumptions in Max Planck's derivation thereof in 1900, was the start of quantum theory. At absolute temperature T, the relative number of x-rays as a function of energy E is

$$N = \frac{gE^2}{e^{E/kT} - 1} \tag{1}$$

per unit E, where g is an arbitrary constant and k is Boltzmann's constant. The total number of photons is

$$\int_0^\infty N\, dE = 2.4041\ g\ (kT)^3; \tag{2}$$

the total energy is

$$\int_0^\infty N\, E\, dE = (\pi^4/15)\ g\ (kT)^4; \tag{3}$$

and the average photon energy is

$$\bar{E} = 2.7012\ kT. \tag{4}$$

As stated above, we adopt

$$kT = 15\ \text{keV}, \tag{5}$$

and therefore a temperature of $T = 174 \times 10^6$ K and average energy $\bar{E}$ = 40.52 keV.

Absorption Coefficients and Fluorescence

For the x-ray energy range under consideration, photons interact with atoms by the Compton and photoelectric effects. Below E = 1022 keV, pair production does not occur and nuclear effects are trivial. The interaction absorption coefficient is thus

$$A = A_C + A_P. \tag{6}$$

For each monoenergetic component, the photon transmission ratio is

$$N_2/N_1 = e^{-At} \tag{7}$$

in a layer of thickness t. Note that the energy absorption coefficient (rather than interaction coefficient) must be used in calculation of the dose in the silicon layers.

In the Compton effect, the x-ray and an electron collide in billiard-ball fashion, with a division of the total momentum and energy. We omit small-angle Compton scattering, where the secondary x-rays move nearly forward at nearly initial energy. In effect, these Compton x-rays (an energy-dependent fraction, about 0.1 of the total) are considered to be unaltered primary x-rays.

In the photoelectric effect, an x-ray of energy E is absorbed by an atom and an electron is liberated, usually from an inner shell. The electron, initially bound with energy B, has kinetic energy E - B. The electron has little range, so the energy is considered to be absorbed. The atom returns to normal by filling the vacancy with an electron (usually) from an outer shell, then that vacancy by an electron further out, and so on until capture of an external electron completes the process.

In this report, the absorption coefficients are interpolated from published values. The Compton effect data are from Hubbell, et al.[1] The photoeffect data are from Scofield[2] at 1.0 keV and greater; values at 0.5 to 1.0 keV are from Veigele.[3] An example (not requiring interpolation) is given in Table I, the case of a 100 keV x-ray on lead.

Each step in the process of filling the photoionization vacancy releases an energy equal to $B_1 - B_2$, the difference in binding energies of the states involved. For K-shell vacancies in the heavy elements, this energy usually appears as an x-ray. Sometimes the energy is given to another electron which emerges as an "Auger electron". In the latter part of this report, we will follow the path of energetic secondary x-rays, both Compton secondaries and K-shell x-rays of high-Z elements. Data regarding K-shell vacancies are thus needed. The fluorescent yields (x-rays emitted per vacancy) are obtained from Wapstra, et al.[4] The relative intensities of K x-ray lines are taken from Storm and Israel.[5] Table II shows these data for lead. The energies of the more intense lines are from Bearden;[6] the others are from the binding energies of Bearden and Burr.[7]

X-Ray Energy Bins

In calculating the dose, the incident x-radiation (Eq. 1) was integrated over bins and given the weighted average energy. Appropriate attenuation by shielding was applied to each bin. In some calculations, an incident energy of 4.184×10^6 keV was split into 68 bins with a total of 103,264 x-rays. (The "4.184" is convenient when the units are calories incident and rads dose.) Of these, 40,919 x-rays are in the 21 bins under 29.20 keV (the K binding energy of Sn); 56,480 are in 31 bins of 29.20 to 88.00 keV (K binding in Pb); and 5865 are in 16 bins of greater energy.

Shielding by Lead

The radiation dose to silicon is shown in Fig. 1 as a function of shielding. (The figure does not include dose due to secondary x-rays.) Within a low-Z spacecraft skin equivalent to 24 mils of Al and a 50 mil Al box wall, the dose is still large. Further aluminum will accomplish little; the low-energy radiation has already been absorbed. If high-Z material is added, the silicon dose drops rapidly, as illustrated by the use of lead here.

Table I. X-ray absorption coefficients for lead (Z = 82) at 100 keV.

		barns/atom	cm^2/gram
Compton		34.04	0.09894
Photo:			
	K shell	1427.9	
	L shell	286.30	
	M shell	67.25	
	Others	20.72	
	Total	1802.2	5.2382

Table II. X-rays produced by a K-shell vacancy in lead (Z = 82).

Transition	E, keV	Relative Intensity
K - L_1	72.144	0.0981
K - L_2	72.804	59.6
K - L_3	74.969	100.
K - M_2	84.450	11.2
K - M_3	84.936	21.6
K - M_4	85.419	0.303
K - M_5	85.520	0.368
K - N_2	87.23	2.65
K - N_3	87.364	5.24
K - N_{45}	87.58	0.177
K - O_{23}	87.92	1.49

X-rays per vacancy = 0.956

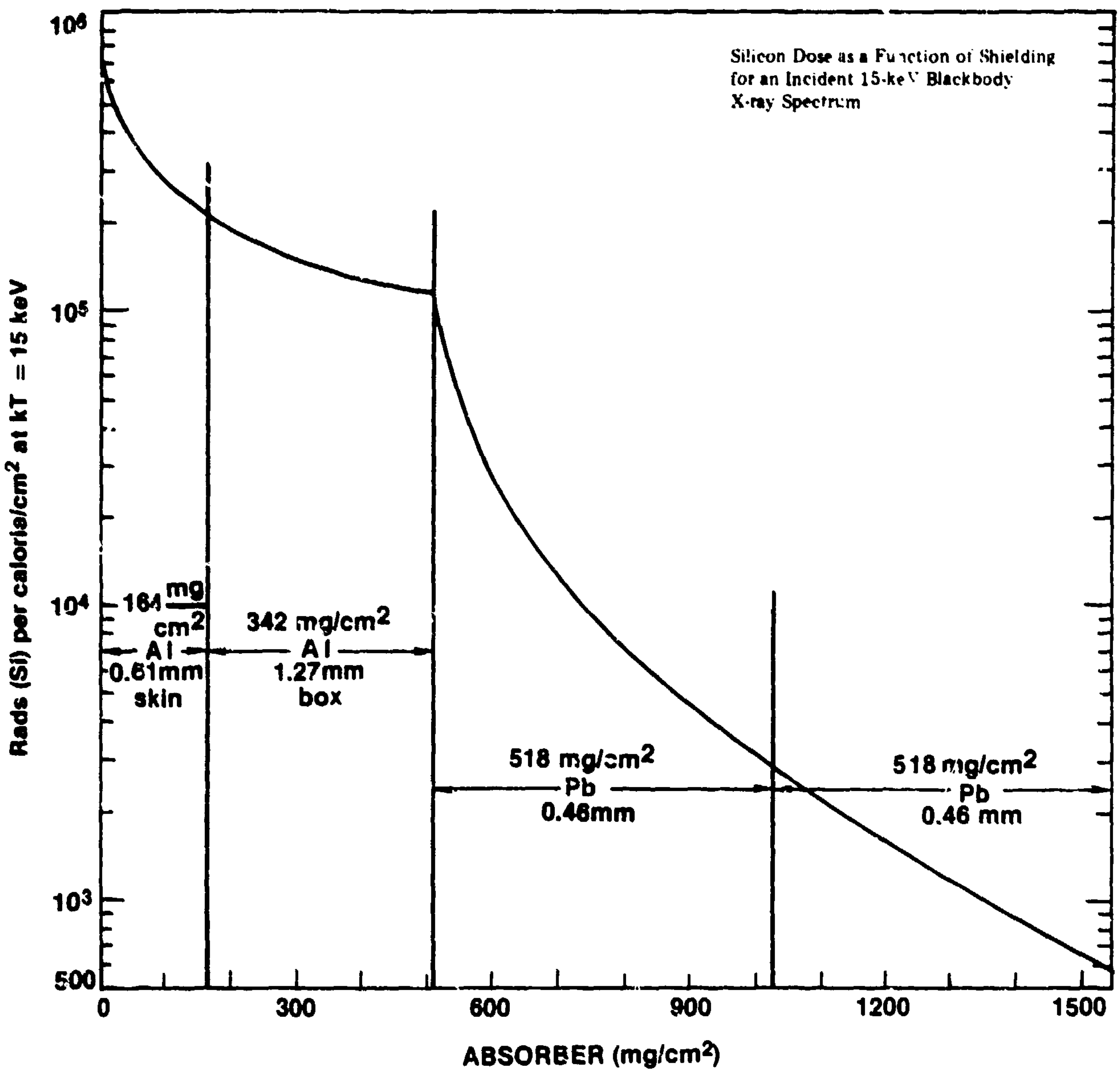


Fig. 1. Rads(Si) due to primary x-radiation of a normally-incident kT = 15 keV Planck spectrum.

The top part of Fig. 2 shows the initial spectrum and the spectrum after traversing 9 mils of lead. It is seen that most of the remaining x-rays are in the range of 40 to 88 keV. The abrupt jumps in the absorption cross sections, shown on the lower part of Fig. 2, clearly show the source of this behavior. These discontinuities occur at the binding energies of the inner-shell electrons of the material.

The Pb absorption cross section is relatively large above 88 keV, primarily due to photoionization of electrons in the K shell. Below 88 keV, the K absorption edge, there is not enough energy to free these electrons; their contribution goes to zero, and the cross section drops sharply. By 40 keV, Pb again has a large cross section, now primarily due to the L electrons. The absorption edges for the three L subshells of Pb appear at about 13 to 16 keV.

Further attenuation of the x-rays by Pb is singularly inefficient -- the remaining x-rays are precisely those which Pb absorbs poorly. Use of a rare earth such as neodymium ($Z = 60$) is indicated.

Use of Several Heavy Elements

It is clear that a proper combination of heavy elements absorbs x-rays better than any single element. It is not clear what form the combination should take -- a separate sheet (or sheets) of each element, bonded sheets, a uniform alloy, perhaps with aluminum cladding. As candidate materials, one can immediately eliminate noble gases ($Z = 54$ and 86), fissionable materials ($Z = 90$ and 92), and radioactive materials ($Z = 61$ and $Z = 84$ up). Chemical and mechanical properties, such as malleability, toxicity, reactivity in dry or wet air, alloy compatability, etc., must be evaluated before a new shielding material is adopted. (These latter properties have been given little consideration here.)

A glance at Fig. 2 indicates that a combination of a few well-separated (in atomic number) elements is desirable. A more quantitative criterion arises when one considers absorption of the dominant penetrating secondary radiation, K x-rays. If lead is the highest-Z element utilized, a study of Table II shows that the other heavy elements should strongly absorb the strong Pb $K\text{-}L_2$ line at 72.8 keV. Table III, which lists the binding energies[7] and $K\text{-}L_2$ x-ray energies,[6] shows that Z must be 75 or less. One pairing in this table is unique; the width[8] of the $K\text{-}L_2$ line of barium, 16.8 eV, is such that it overlaps the tellurium K binding energy.

Pb + Ta + Dy

The silicon doses from x-rays were calculated with various shields of lead (with 4 percent antimony), tantalum, and dysprosium, employing a programmable HP-97 calculator. In all cases, 0.5 g/cm^2 of aluminum alloy (1.2 percent manganese) was also used. For a small amount of high-Z shielding, Pb, with the largest absorption coefficient below 53.8 keV, is best. As one increases the shielding, the point is reached where any heavy element will absorb most of the low energy x-rays, and the absorption at increasingly higher energies is most important. In turn, Dy becomes best, then Ta, and finally Pb again. At all thicknesses, a proper mixture is better. Some of the calculated doses are included in Table IV.

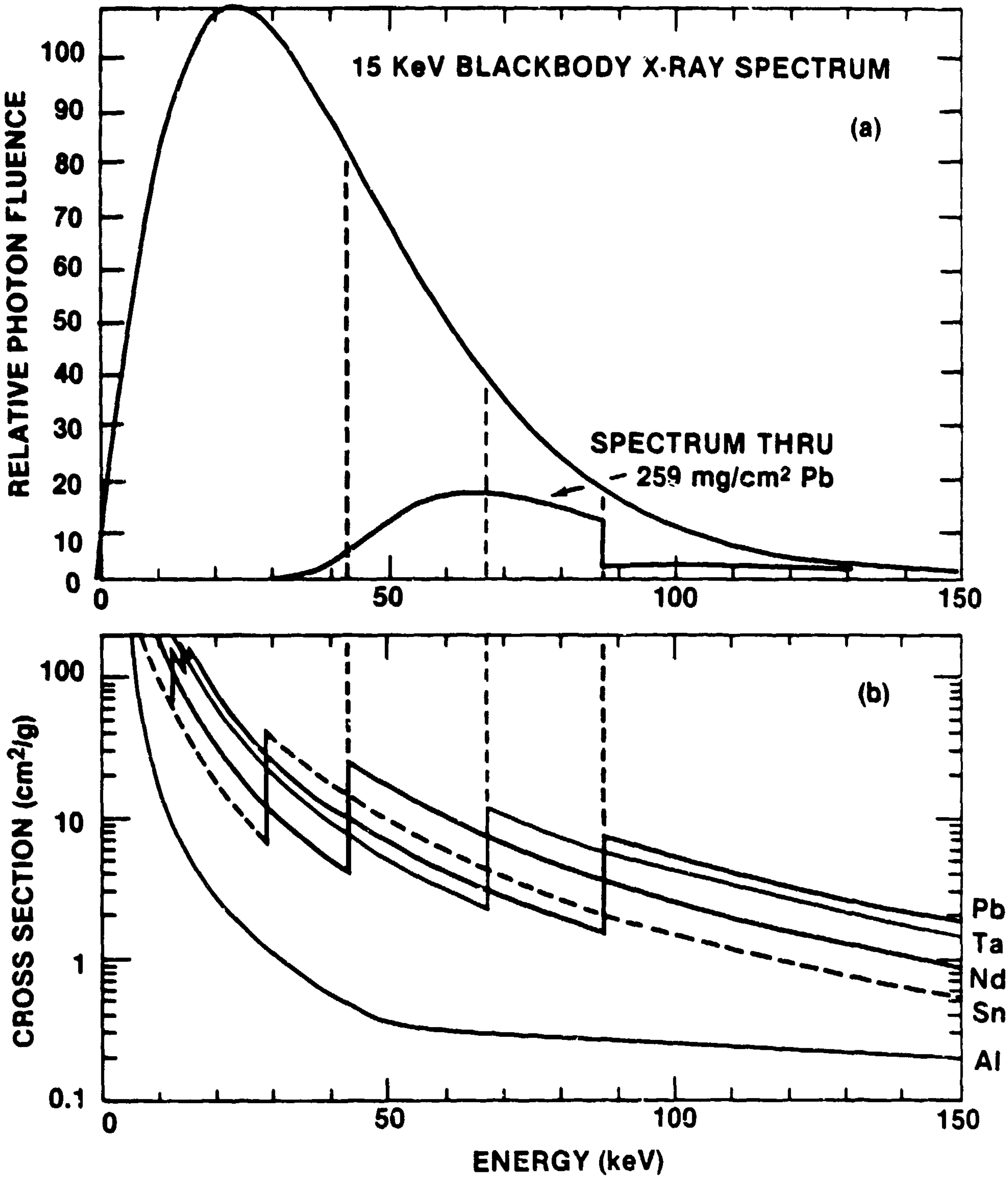


Fig. 2. (a) Shapes of a kT = 15 keV Planck spectrum and of the residual spectrum after passing through 0.009-inch of lead. (b) Interaction absorption coefficients (cross sections) versus energy for five elements.

Table III. Energies, in keV, of K-shell electron binding and of the $K - L_2$ x-ray.

Z	Element	K
83	Bi	90.53
82	Pb	88.00
81	Tl	85.53
80	Hg	83.10
79	Au	80.72
78	Pt	78.39
77	Ir	76.11
76	Os	73.87
75	Re	71.68
74	W	69.52
73	Ta	67.42
72	Hf	65.35
71	Lu	63.31
70	Yb	61.33
69	Tm	59.39
68	Er	57.49
67	Ho	55.62
66	Dy	53.79
65	Tb	52.00
64	Gd	50.24
63	Eu	48.52
62	Sm	46.83
(61	Pm	45.18)
60	Nd	43.57
59	Pr	41.99
58	Ce	40.44
57	La	38.92
56	Ba	37.44
55	Cs	35.98
(54	Xe	34.56)
53	I	33.17
52	Te	31.8138
51	Sb	30.49
50	Sn	29.20
49	In	27.94
48	Cd	26.71
47	Ag	25.51

Z	$K - L_2$
83	74.81
82	72.80
81	70.83
80	68.89
79	66.99
78	65.12
77	63.29
76	61.49
75	59.72
74	57.98
73	56.28
72	54.61
71	52.97
70	51.35
69	49.77
68	48.22
67	46.70
66	45.21
65	43.74
64	42.31
63	40.90
62	39.52
(61	38.17)
60	36.85
59	35.55
58	34.28
57	33.03
56	31.8171
55	30.63
(54	29.46)
53	28.32
52	27.20
51	26.11

The case of 0.8 g/cm^2 of heavy elements was given detailed study. Figure 3 shows rads(Si) as a function of mixture, at steps of 10 percent by mass. The optimum case and the corner points of Fig. 3 are examined in Fig. 4. Absorption of parts of the spectrum varies tremendously -- note that the absorption coefficient is in the exponent in Eq. (7). (In fact, the 54-67 keV band for Z = 66 is smaller, 0.17 mm, than can be shown in Fig. 4.) The mixture, by producing about the geometric mean dose for each component, produces the smallest total dose.

Six Elements

By the use of more elements, a moderate further reduction of dose can be achieved. In order to meet the criterion on K-L_2 x-ray absorption (above and Table III), elements must be adequately spaced in Z. Calculations were made with elements 82, 75, 68, 62, 57, and 51. For the three thicknesses chosen, the lightest element, Sb, was not useful. At 0.8 g/cm^2, the optimum mix (.17 Pb, .195 Re, .195 Er, .175 Sm, .065 La) yields 370 units. This is a 17 percent reduction from the Pb+Ta+Dy minimum of 448 (Fig. 3). With greater thicknesses, lanthanum is not useful. At 1.1 g/cm^2, the optimum mix (.38 Pb, .28 Re, .26 Er, .18 Sm) yields 135 units. At 1.4 g/cm^2, the optimum mix (.62 Pb, .36 Re, .31 Er, .11 Sm) yields 61 units, 12.5 below 88 keV and 48.2 above.

Sequence of Elements

The sequence of elements is important. Paradoxically, the high-Z material should be neither on the inside nor on the outside. If on the inside, the numerous short-range photoelectrons produced by x-ray absorption in heavy elements would yield a large dose in the electronics -- an effect called high-Z enhancement. A modest layer of aluminum will correct this. Fortunately, the aluminum boxes containing the electronics normally provide this layer inside high-Z shielding, but does not protect against enhancement by high-Z solder at the electronics. If on the outside, the high-Z material will be struck by trapped electrons of full energy, and about 7 times (for lead) as many bremsstrahlung x-rays will be produced as in a corresponding layer of aluminum. It is therefore advisable to put most of the aluminum outside of the heavy elements. The electrons then have reduced energy when they reach the high-Z material, and they consequently produce much less bremsstrahlung.

When the dose due to secondary radiation is considered, the sequence of heavy elements is also of consequence. For given elements and total mass, the ideal material is an alloy of graduated composition. In the absence of this metallurgical marvel, a uniform alloy would do well -- and it could not be installed upside down. Another good solution would be alternating layers of the elements used, as studied in the next section.

Dual-Purpose Shield

When there is an x-ray burst from an exoatmospheric nuclear weapon, electrons will be trapped in the geomagnetosphere. Thus, the need of an x-ray shield implies the need of an electron shield. The initial particles are, primarily, those emitted in the beta decay of short-lived fission products. This spectrum has considerably higher average energy than that of

Tantalum

1122

795 1007

655 716 911

608 590 651 830

609 546 538 600 768

638 546 499 500 564 724

684 570 499 466 477 546 703

743 610 520 467 450 473 551 713

448

812 660 555 488 454 454 493 587 766

892 720 600 521 476 463 484 548 671 883

984 789 653 563 510 490 503 555 656 827 1101

Dysprosium Lead

Fig. 3. Rads(Si) from 1 calorie/cm^2 of kT = 15 keV primary x-rays through 0.5 g/cm^2 aluminum alloy (98.8% Al, 1.2% Mn) and 0.8 g/cm^2 heavy elements. The corners of the triangle show values for Ta, Dy, and hard lead (96% Pb, 4% Sb). Each step corresponds to a 10% change in the mix. The minimum is at 0.20 g/cm^2 Ta, 0.26 Dy, and 0.34 lead.

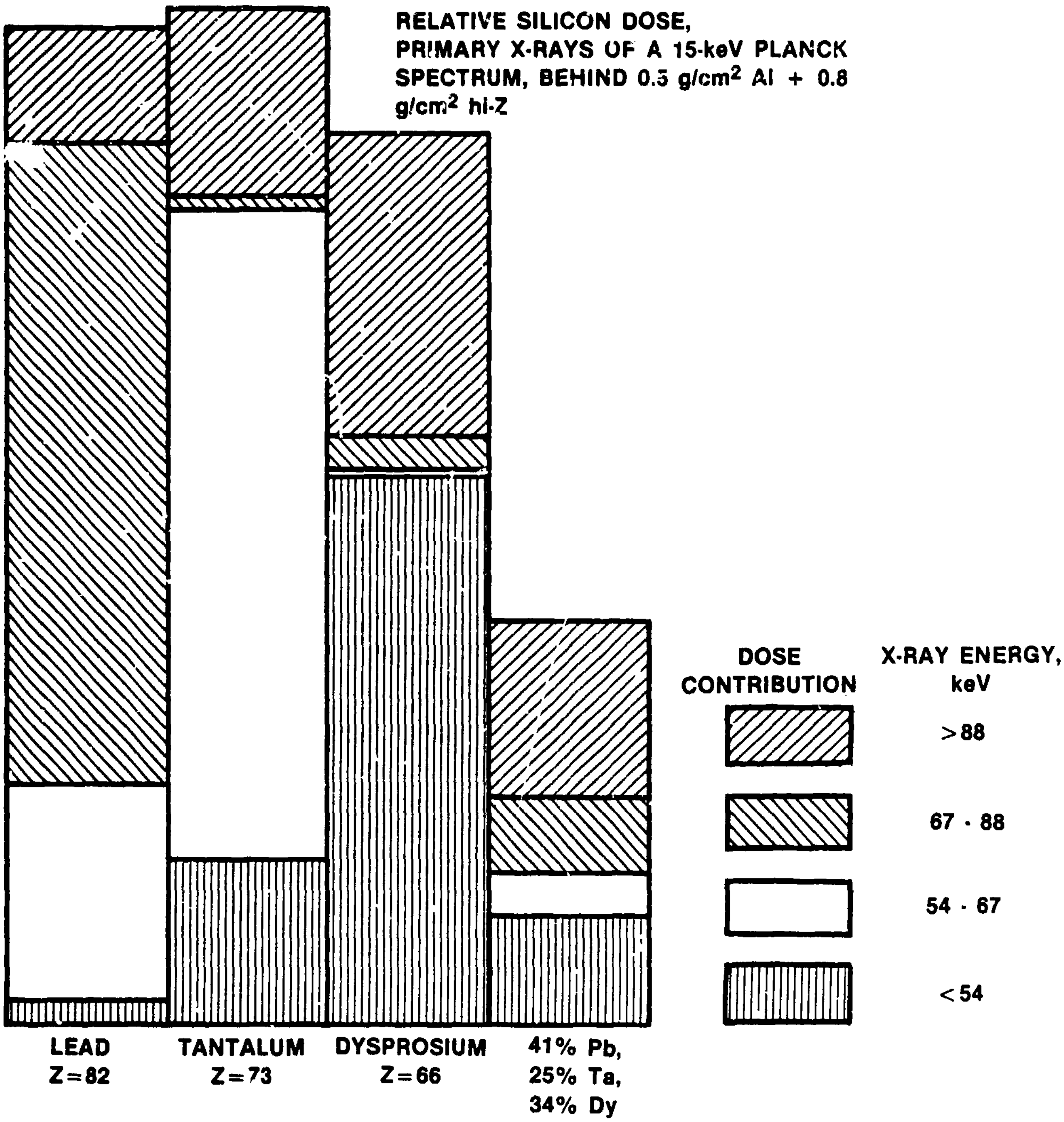


Fig. 4. Relative silicon dose due to the primary x-radiation of a 15 keV Planck spectrum, with 0.5 g/cm^2 of aluminum alloy and 0.8 g/cm^2 of high-Z element shielding.

all fission beta particles, has about 4 or 5 percent electrons above 4 MeV, but has almost no electrons above 9 MeV.[9] The trapping process does not accelerate electrons, but it considerably increases the proportion of electrons at high energy.

Further x-ray calculations were made with the spacecraft shielding model shown in Fig. 5. The outer 0.9 g/cm^2 of Al stops normally-incident (i.e., is the pathlength[10,11] of) electrons of 1.53 MeV, and the entire shield, 2.97 MeV. An electron of 4 MeV produces, on the average, 134 keV of bremsstrahlung[10] when stopped in pure Al or 738 keV in tungsten. If the shield were of these elements, and as shown, 4 MeV electrons entering at 41.5° (arc cos 0.749) from normal incidence would just be stopped and would produce 305 keV of bremsstrahlung. The dose due to isotropic 4 MeV electrons at this depth, 0.749 pathlengths, is 7.5 percent of that near the surface.[12]

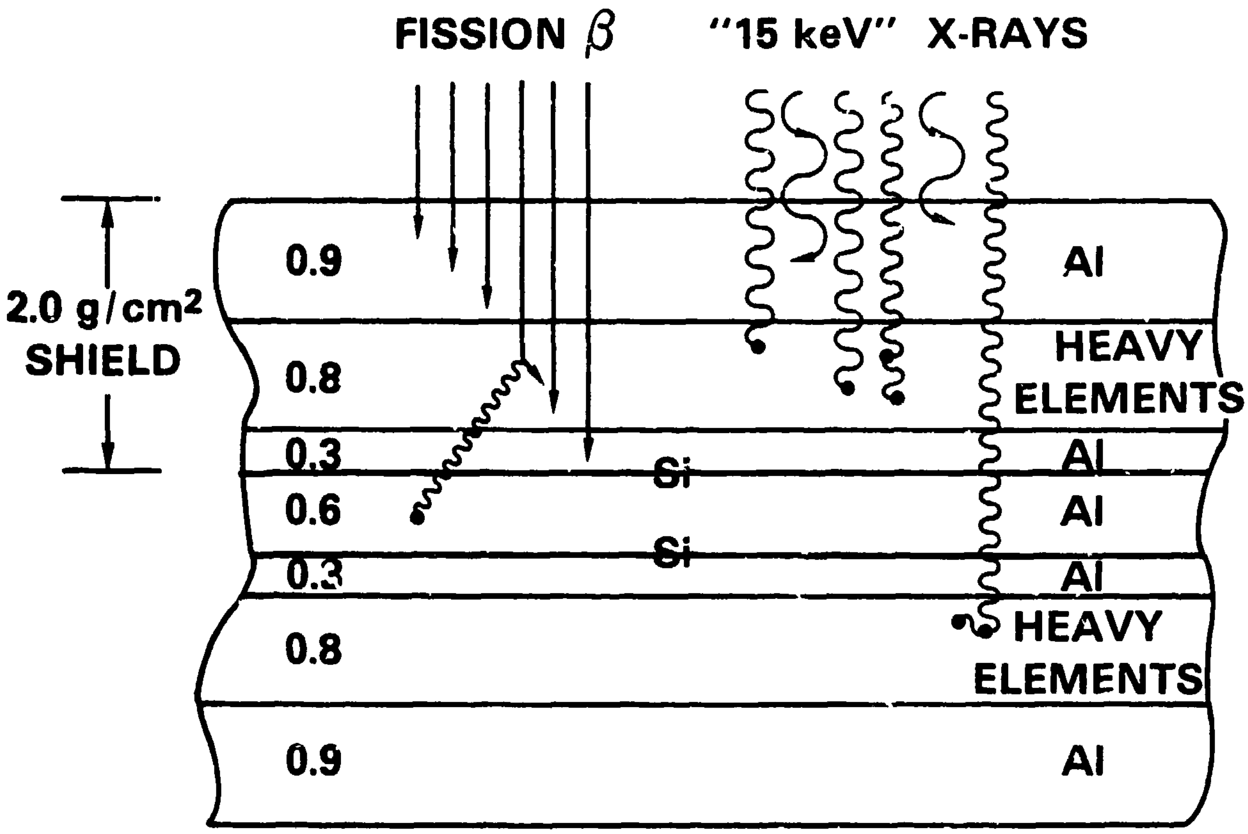
Dose with Secondary X-Rays

We have shown the reduction in dose with the use of multi-element shields, but only in regard to the dose attributed to primary radiation. Although a similar advantage for secondary radiation dose is obvious, it seems desirable actually to calculate the effect. The techniques used here for primary radiation are simple but tedious; they become complex and burdensome when secondary radiation is followed. Nevertheless, four cases were calculated for the geometry of Fig. 5; the electronics core, equivalent to 0.6 g/cm^2 of Al alloy, is present for only the last case. For mixed heavy elements and this thickness, the previously-ignored dose due to secondary x-rays can exceed the primary dose, as shown in Table IV.

The runs were made in the order of Table IV, with composition and other changes made in each run. The secondary (and tertiary) radiations produced in a layer (0.06 to 0.12 g/cm^2 for high-Z, 0.3 or 0.9 for Al) are distributed among quantized angles, initially nine but reduced to six -- 0°, 2 others forward, and 3 retrograde -- in the last two runs. In practice, the Compton cross section assigned to 0° (about 10.6 percent of the total at 50 keV) was omitted, and these x-rays continued as "primaries". The fact that secondary radiations are going in all directions makes them considerably less penetrating than equally-energetic primary x-rays.

In the first run, secondary photons of 21 keV up were followed. The secondary dose was dominated by the x-rays of the innermost heavy element. It was evident that low-energy Compton secondaries could be ignored and the requirement was raised to 32 keV up, then to 35 keV up (in 19 energy bins) for the last two runs. The K x-rays were bunched into 2 Pb, 2 Ta, and 3 Dy lines for the last run.

In the last two runs, the rule of highest-Z on the outside was violated as half and then 2/3 of the Dy was placed outside the Pb and Ta. The Dy x-ray dose still exceeded that of all other secondaries combined. Even more interleaving is needed; a uniform high-Z mixture might be closer to optimum than any reasonable number of sheets.



SEMI-INFINITE PLANE SHIELDING

Fig. 5. Cross section of a hypothetical satellite, with thickness shown proportional to areal density. Shielding is provided against trapped particles and x-rays. Symmetry is used in tracing retrograde secondary x-rays.

Table IV. Silicon dose, in rads per calorie/cm^2, for 15-keV Planck radiation. Except for sums, only primary x-rays are considered.

g/cm^2 Al (1.2% Mn)	0.5	0.5	0.5	0.5	0.5	0.5	1.2
g/cm^2 heavy elements	0.5	0.8	1.1	1.4	1.9	3.2	0.8
Al (Mn) only	112K						59K
Pb, Z=82 (4% Sb, Z=51)	2930	1102	483	230	76	6.5	969
Ta, Z=73	3360	1122	439	191	58	6.5	958
Dy, Z=66	3240	984	375	170	64	13.0	819
Five element mix		370					
Four element mixes			135	61			
62.5% Pb(Sb), 37.5% Ta	2450	702					608+686 = 1294
50% Pb(Sb), 30% Ta, 20% Dy	1950	473					411+773 = 1184
45% Pb(Sb), 25% Ta, 30% Dy		449					391+604 = 995
41% Pb(Sb), 25% Ta, 34% Dy	1870	448	149	66	25.5	4.9	391+565 = 956

Table V. Rads(Si) per calorie/cm^2 of kT = 15 keV Planck radiation for the final case of Table IV. The geometry is that of Fig. 5, with 0.18 g/cm^2 Dy on the outside, 0.33 of Pb alloy, 0.20 of Ta, and 0.09 of Dy. Dose due to forward and reverse x-rays are shown separately for Si devices at 2.0 and 2.6 g/cm^2 from the top surface.

First Si Devices			Photon Bin	Last Si Devices			Bottom Surface
Fore	Aft	Total	(keV)	Fore	Aft	Total	Fore=Total
			PRIMARIES				
		29.2	Over 160			27.4	11.4
		90.3	117-160			84.0	15.5
		60.9	88-117			56.1	2.5
		75.0	67.42-88			67.7	1.6
		40.4	53.79-67.42			35.3	0.3
		95.1	~ 40-53.79			78.2	0.7
391.0		391.0	Subtotal	348.7		348.7	31.9
			COMPTONS				
13.0	15.3	28.3	Over 88	29.2	9.8	39.0	5.7
10.5	19.2	29.7	67.42-88	18.2	7.4	25.6	1.7
14.0	14.9	28.9	53.79-67.42	19.7	4.8	24.5	0
35.3	42.5	77.8	42.37-53.79	43.4	17.1	60.5	0.1
9.8	20.8	30.6	~37-42.37	17.9	6.0	23.9	0
82.5	112.7	195.2	Subtotal	128.4	45.1	173.5	7.5
			K X-RAYS				
10.0	0.5	10.5	Pb	8.7	0.6	9.3	1.7
45.4	5.5	50.9	Ta	36.7	6.8	43.5	0.2
248.4	59.8	308.2	Dy	148.3	103.8	252.1	9.0
303.8	65.8	369.5	Subtotal	193.7	111.2	305.0	10.9
777	179	956	GRAND TOTAL	671	156	827	50

The results of the final run, the only one with a core representing low-Z "electronics", are presented in Table V. The dose decreases from 956 to 827 rads(Si) per calorie/cm^2 across this region and is still 50 units at the bottom surface. The Compton dose at the first silicon devices is astonishing -- because of the proximity of more Al behind this layer, backward-moving Comptons exceed forward-moving ones.

Summary

We have shown that a mixture of heavy elements provides better shielding against a continuous x-ray spectrum than any single element. For a kT = 15 keV Planck spectrum and 0.5 g/cm^2 aluminum shielding, an optimum mixture of 0.8 g/cm^2 of lead, tantalum, and dysprosium reduces the dose due to primary x-rays to less than half that for the same mass of any of them. At 1.4 g/cm^2, an optimum mixture cuts the dose even more relative to a single element.

When the dose due to secondary x-rays is included, the superiority of mixed heavy elements remains.

Use of optimum high-Z shielding can provide better shielding for given mass or the same shielding for less mass. Such shields should be included in the techniques used to protect spacecraft from both nuclear tests and wartime threats.

The optimum mixture must meet certain simple conditions relating to atomic energy levels. Within these conditions, chemical and metallurgical properties dictate acceptable elements and mixtures. Although the results here are sufficient to show the general requirements of a good mixture, more sophisticated computer procedures and specific spacecraft designs should be employed in evaluating proposed mixtures.

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